NuFACT 2022 - Snowbird, UT

WG1-WG2: Constraining XSec Systematics/XSec Tuning

Structure Functions and Tau Neutrino Cross-Section at DUNE Far Detector

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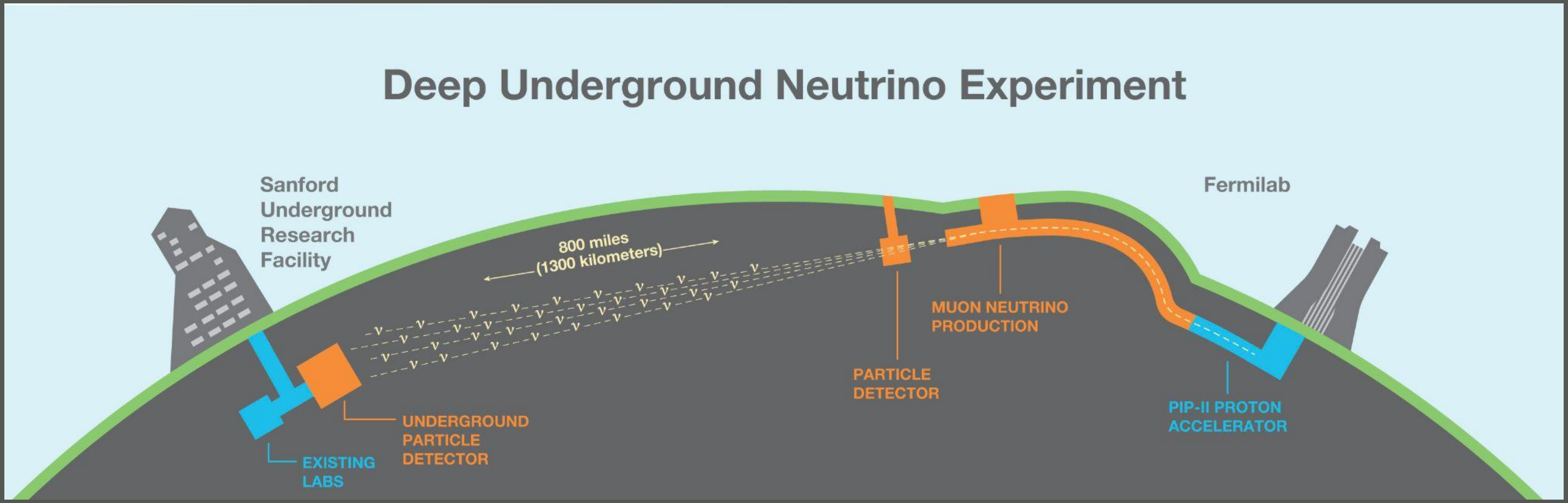
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

The Deep Underground Neutrino Experiment (DUNE)

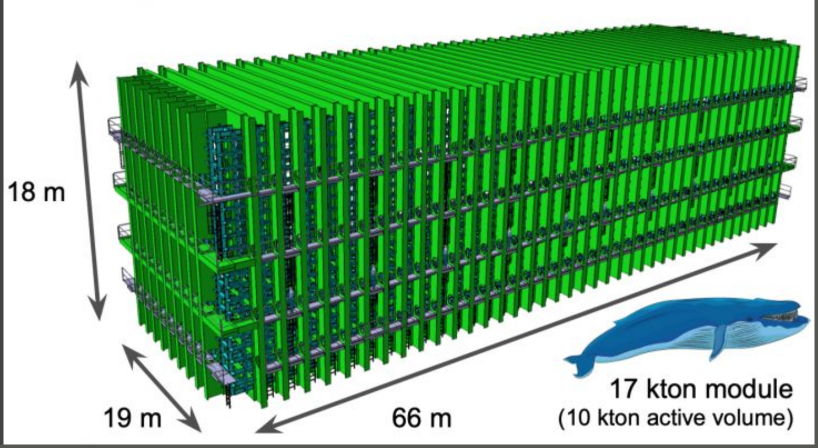


- Currently under construction.

- A broad set of topics to being pinned down at DUNE, it will be able to constrain the three-massive-neutrinos paradigm by providing complementary measurements to those from the ν_e - appearance and ν_μ - disappearance channels.

Far Detector

- 1300 Km baseline
- Liquid argon time projection chamber (LArTPC) technology →high resolution neutrino interaction imaging
- 4x17 kton LArTPC modules.



NuTau at DUNE - What we can learn from ν_τ ?

DUNE is the only upcoming neutrino experiment expected to be able to **collect a larger** sample of oscillated ν_τ **events** from a beam than all existing experiments.

ν_τ data can help to understand non trivial questions, summarized in the Snowmass Whitepaper arXiv:2203.05591

Current generation of neutrino experiments provides nearly complete description of three flavor paradigm, but:

● Almost all knowledge of tau neutrino sector is taken from:

→ Lepton universality for cross sections

→ PMNS unitarity for oscillations

● Critical that these assumptions are tested

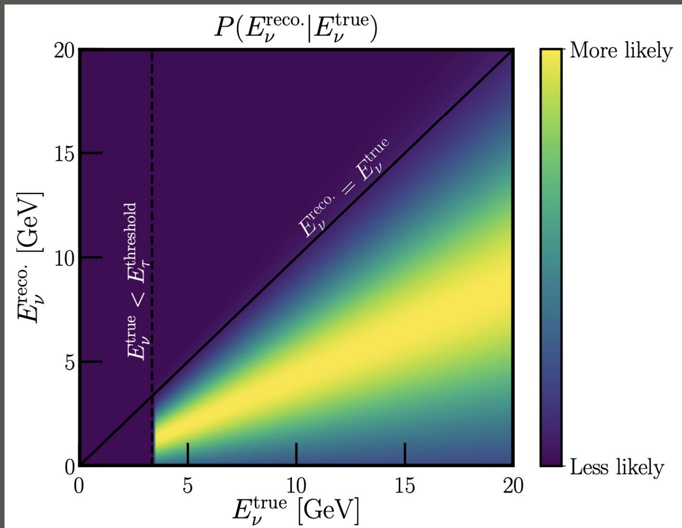
Why cross sections are important?

- **Neutrino interactions** (cross section) → major contributor of systematic uncertainties in oscillation measurements (T2k, NOvA).
- E_ν & ν-nucleus interactions relies on **reconstruction techniques** either based on **kinematics** (T2K/HK) or **calorimetric methods** (DUNE/NOvA/SBN) and both requires reliable predictions from **interaction models.**
- Extraction of **oscillation parameter** is biased by the interaction model.

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij}\ \sin^2\left(\frac{\Delta m^2_{ij}}{4}\frac{L}{E_\nu}\right)$$

$$N^{\alpha\to\beta}_{FD}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu)\times\sigma^i_\beta(E_\nu)\times P(\nu_\alpha\to\nu_\beta)\times\epsilon_\beta(E_\nu, E_{\nu,rec})$$

Tau Neutrino Interactions: due to the large mass of the τ ± relative to the e ± and μ ±, the threshold for this process to occur is 3.5 GeV.

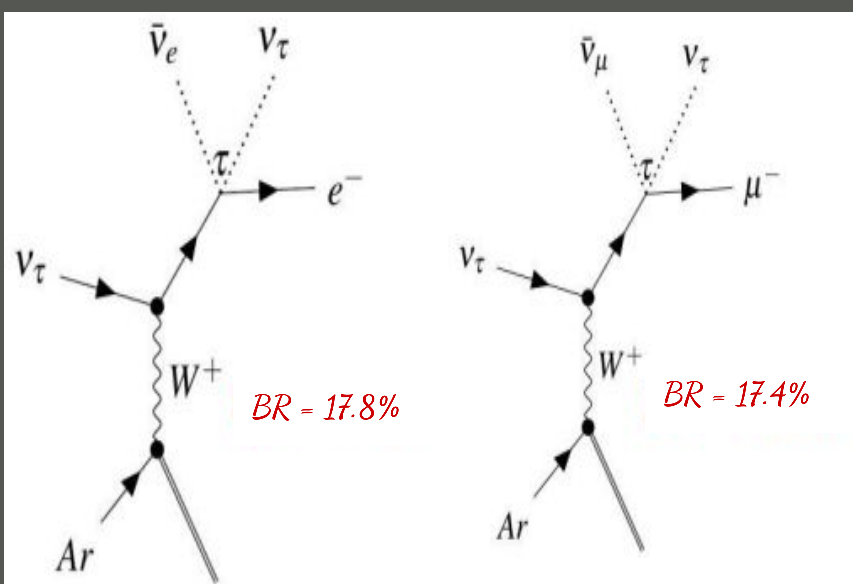


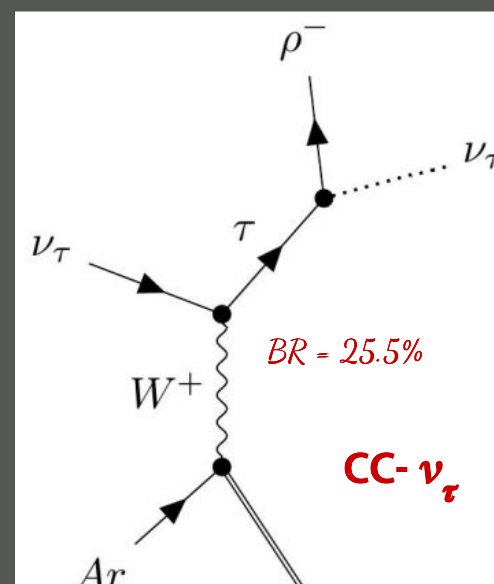
A.Gouvea, K. Kelly, G.Stenico, P.Pasquini
PhysRevD.100.016004

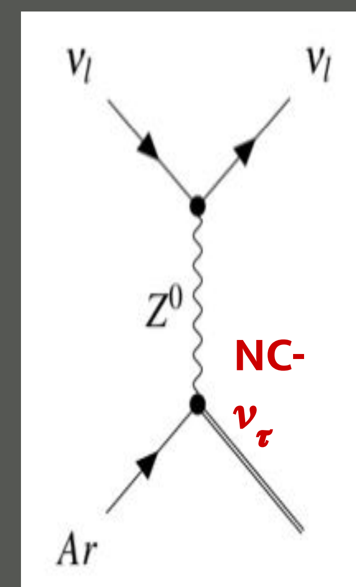
Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
other	5.7%

Dominant decay modes of τ− Kaonic decays and others go into the "other" category. arXiv:2007.00015

Challenge: ν_τ reconstruction and the background rejection from NC.







DIS CC-ν_τ Cross-section

Albright, Jarlskog '75 Paschos, Yu '98 Kretzer, Reno '02

$$\frac{d^2\sigma_A}{dxdy} = \frac{G_F^2 M_N E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\Big\{\Big[y^2x + \frac{m_l^2 y}{2E_\nu M_N}\Big]F_{1A}(x,Q^2) + \Big[\Big(1-\frac{m_l^2}{4E_\nu^2}\Big) - \Big(1+\frac{M_N x}{2E_\nu}\Big)y\Big]F_{2A}(x,Q^2)$$

$$\pm\Big[xy\Big(1-\frac{y}{2}\Big) - \frac{m_l^2 y}{4E_\nu M_N}\Big]F_{3A}(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x}F_{4A}(x,Q^2) - \frac{m_l^2}{E_\nu M_N}F_{5A}(x,Q^2)\Big\}.$$

The scaling variables $x(=\frac{Q^2}{2p\cdot q})$ and $y(=\frac{\nu}{E_\nu}=\frac{q_0}{E_\nu})$ lie in the range:

A lepton mass correction appear $\longrightarrow$ limits x,y

$$\frac{m_l^2}{2M_N(E_\nu - m_l)} \le x \le 1 \qquad \text{and} \qquad a-b \le y \le a+b,$$

where

$$a = \frac{1 - m_l^2\Big(\frac{1}{2M_N E_\nu x}+\frac{1}{2E_\nu^2}\Big)}{2\Big(1+\frac{M_N x}{2E_\nu}\Big)} \qquad \text{and} \qquad b = \frac{\sqrt{\Big(1-\frac{m_l^2}{2M_N E_\nu x}\Big)^2 - \frac{m_l^2}{E_\nu^2}}}{2\Big(1+\frac{M_N x}{2E_\nu}\Big)}.$$

arXiv:1007.1966

$\longrightarrow$ A **structure function (SF)** characterize the internal structure of the nucleon

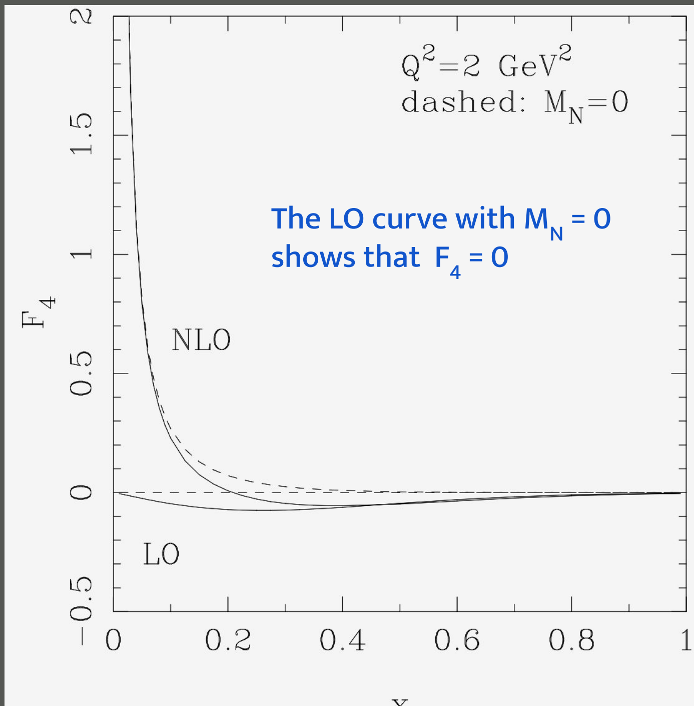
$\longrightarrow$ The **contributions of the SF to the cross-section** are functions of charged lepton mass.

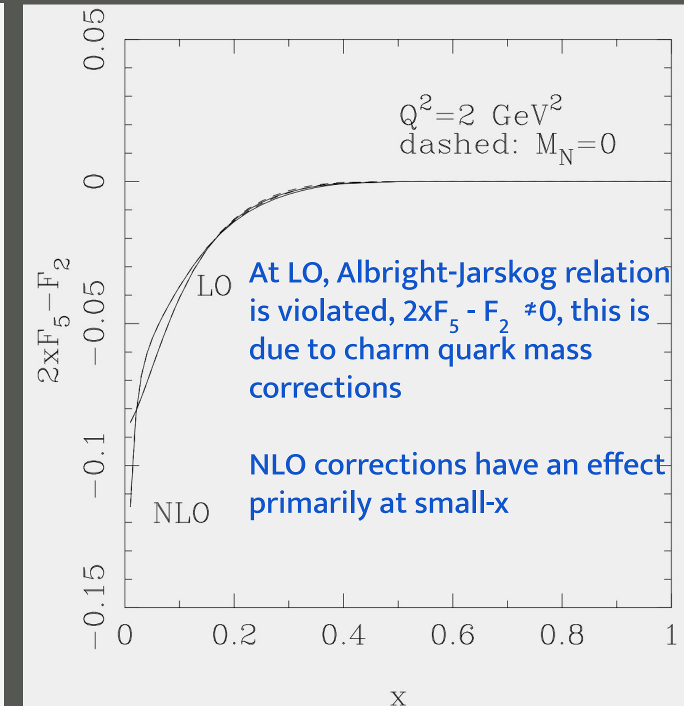
$\longrightarrow$ In the limit $m_l^2 \longrightarrow 0$ only F_1, F_2 and F_3 contribute, $m_l^2/(M_N E_\nu)$.

$\longrightarrow$ Given the higher mass value of the τ lepton, F_4 and F_5 pointed out by **Albright-Jarlskog (AJ) relations** occur only in heavy lepton (τ) scattering, Nucl. Phys. B 84, 467 (1975) and are negligible for ν_μ and ν_e, but become important for ν_τ cross-section.

A look to F_4 and F_5 Structure Functions

M. H. Reno - PhysRevD.74.033001
arXiv:1007.1966v1





Structure functions

The Callan-Gross relations:

$$2xF_1 = F_2$$
$$-xF_3 = F_2$$

At LO, in the limit of massless quarks & target hadrons, Albright-Jarlskog pointed:

$$2xF_5 - F_2 = 0$$

F_4 = 0, also holds when the nucleon target is replaced by a lepton target.

$$F_{1N}(x) = W_{1N}(\nu, Q^2)$$
$$F_{2N}(x) = \frac{Q^2}{2xM_N^2} W_{2N}(\nu, Q^2)$$

$$F_{3N}(x) = \frac{Q^2}{xM_N^2} W_{3N}(\nu, Q^2)$$
$$F_{4N}(x) = \frac{Q^2}{2M_N^2} W_{4N}(\nu, Q^2)$$

$$F_{5N}(x) = \frac{Q^2}{2xM_N^2} W_{5N}(\nu, Q^2).$$

- At NLO, *F_4 ~ 1% of F_5* , AJ relations are good approximations to the NLO result, arXiv:hep-ph/0605295.
- Both of the figures show that in evaluations of the total charged current cross section, the naive AJ relations are good approximations to the NLO results. This is true at low energies, where ν_τ cross-section does not probe small-x and at high energies where F_4, F_5 are suppressed, anyway.

Truth Level Studies: Nature of F_5 and Hypothesis of $F_4 = 0$, $F_5 = 0$ for higher values of x.

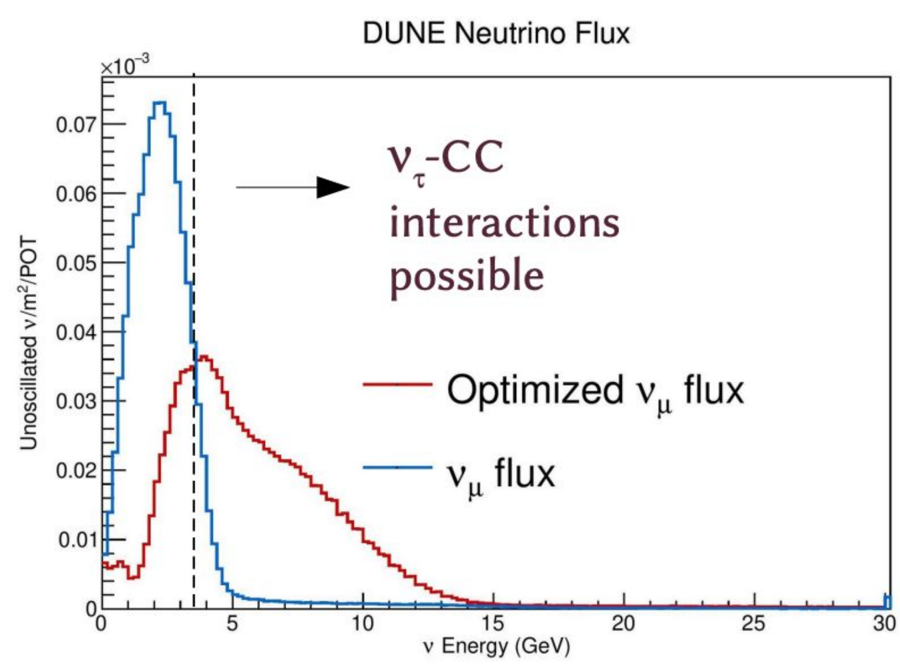
- GENIE 3.0.6 truth Information
- Using DUNE far detector geometry (Argon 40)
- Tau optimized flux

- CP optimized (3 horns configuration)

- Low energy
- Default starting configuration

- Tau-optimized (2 horns configuration) - future upgrade, under investigation

- High energy spectrum
- Possible configuration after CP program has completed

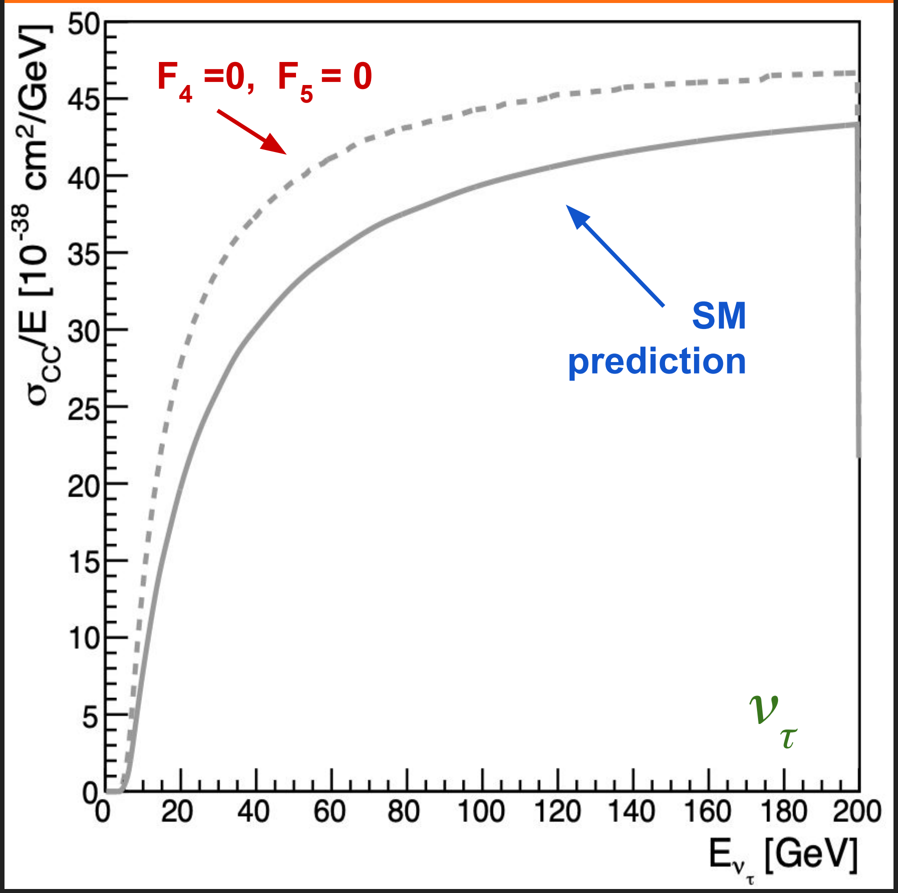


Expected counts/year:

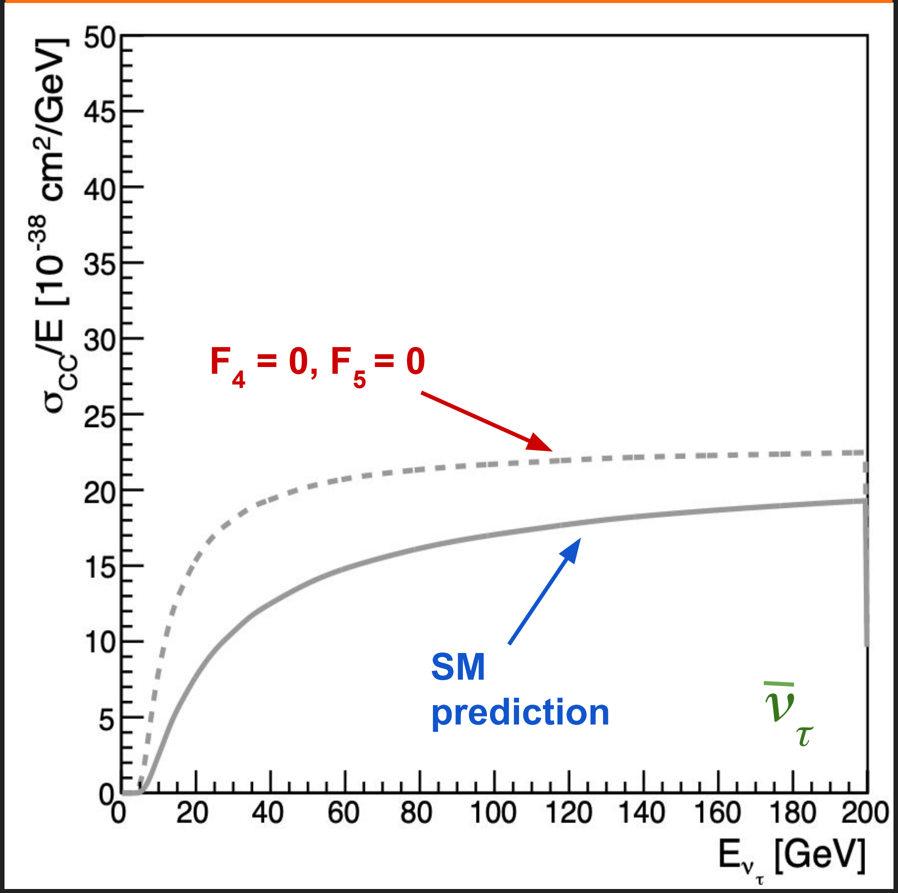
~ 30 $\overline{\nu_\tau}$ in CP-optimized neutrino mode
~ 130 ν_τ in CP-optimized neutrino mode
~ 800 ν_τ in Tau-optimized neutrino mode

Notice the difference between the **cross-sections in the $F_4 = 0$, $F_5 = 0$** hypothesis and the standard model prediction

GENIE 3.0.6 CC-NuTau Cross Section



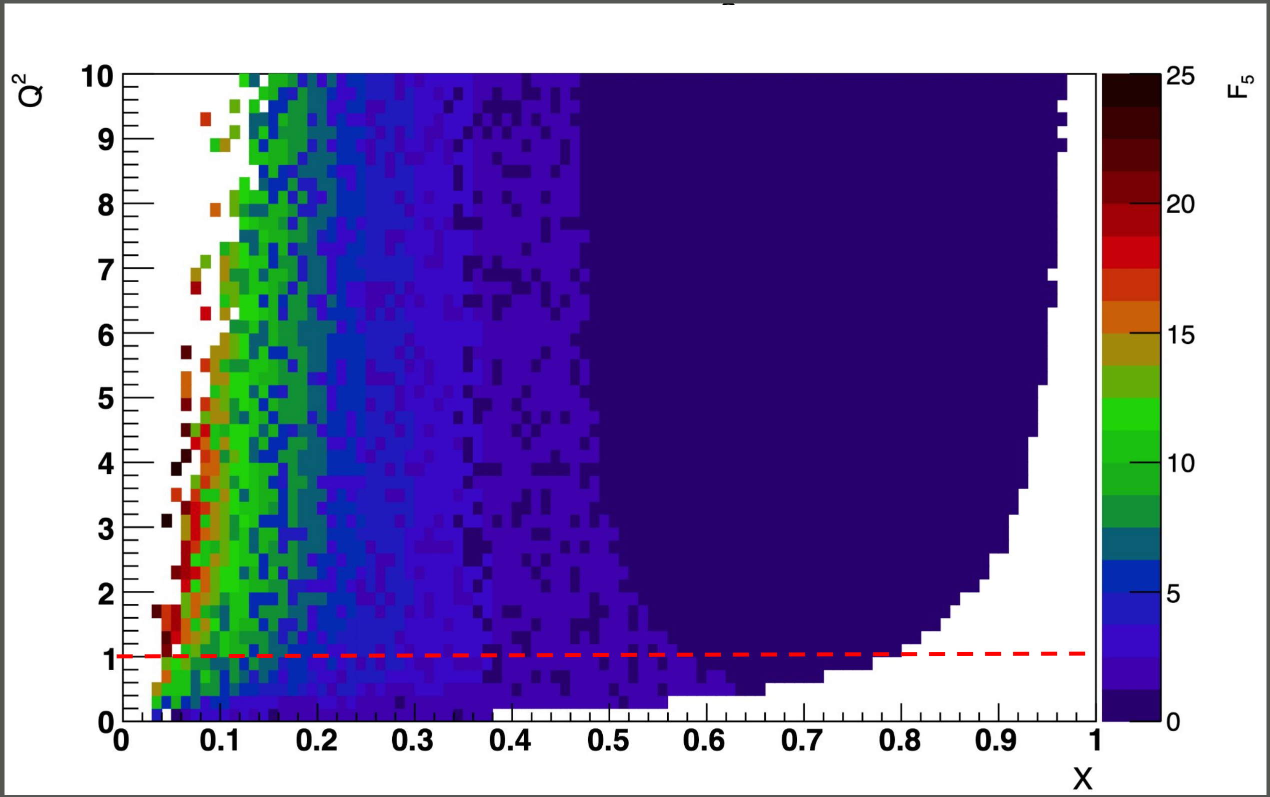
GENIE 3.0.6 CC- Anti NuTau Cross-Section



$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\right),$$

Nature of F_5 (x, Q^2)

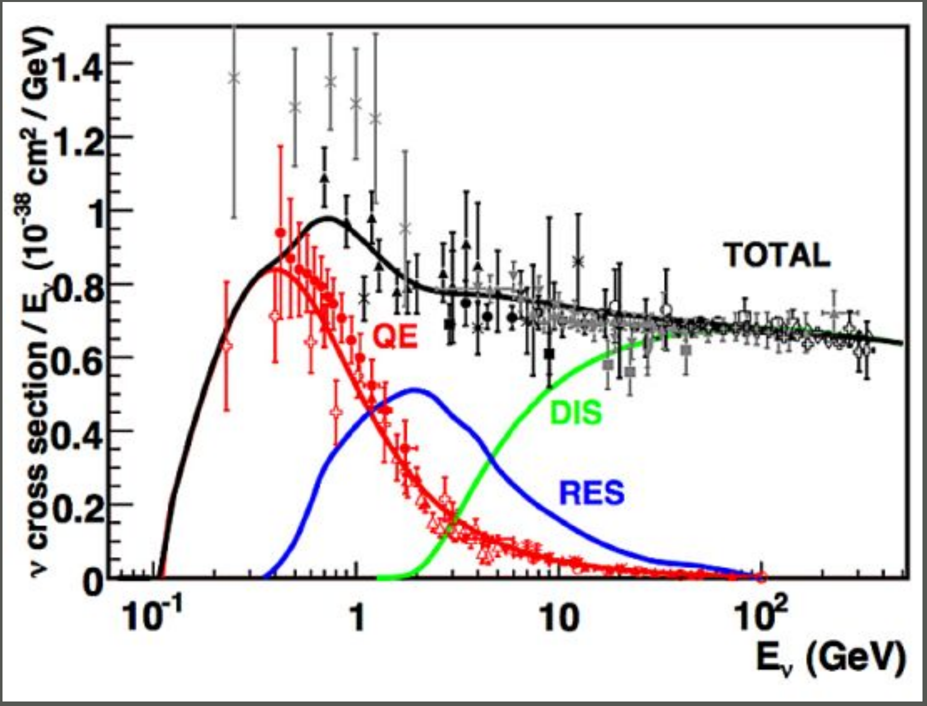
- This is F_5 in terms of x and Q^2, its effect is in all [x,Q^2] phase space.
- At lower X , F_5 values are high.
- Below Q^2 =1 , non-perturbative
- Above Q^2 =1 , perturbative



$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$

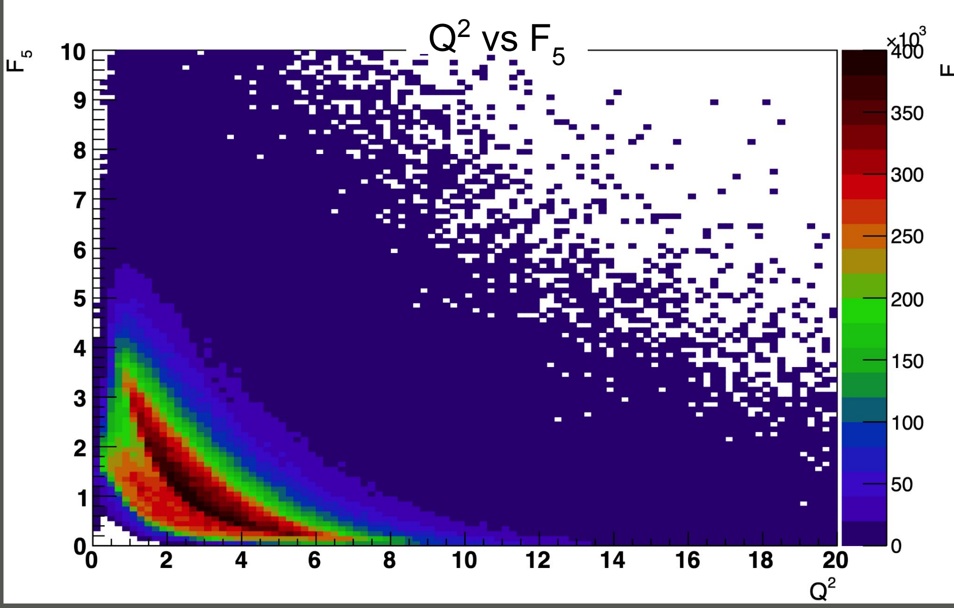
Nature of F_5 (x, Q^2)

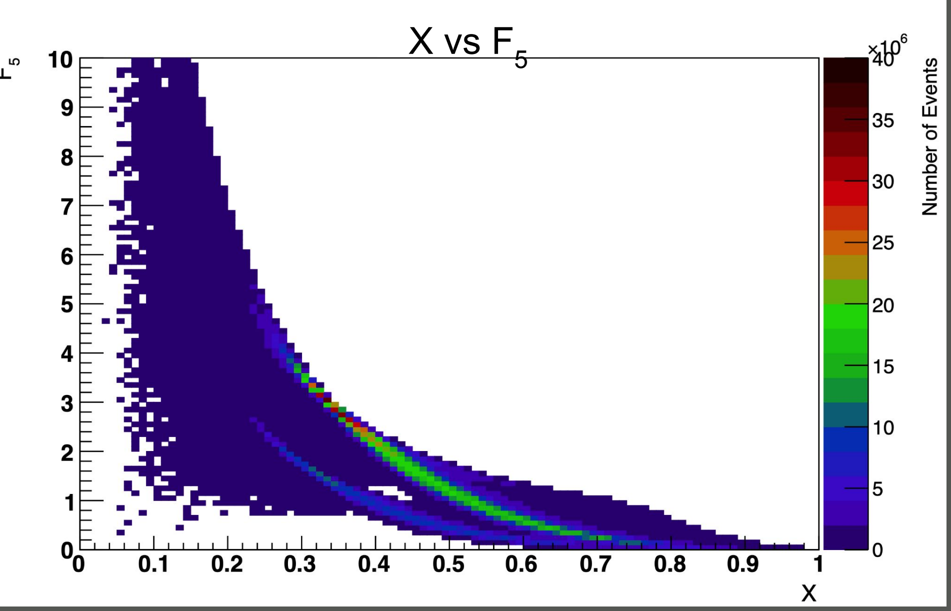
This is F_5 in terms of x and Q^2, its effect is in all [x,Q^2] phase space.



Nuclear models rely → approximations, which are valid in specific kinematics and for specific process.

For F_5 is sensitive in values for x and Q^2 that wrap different interactions models.



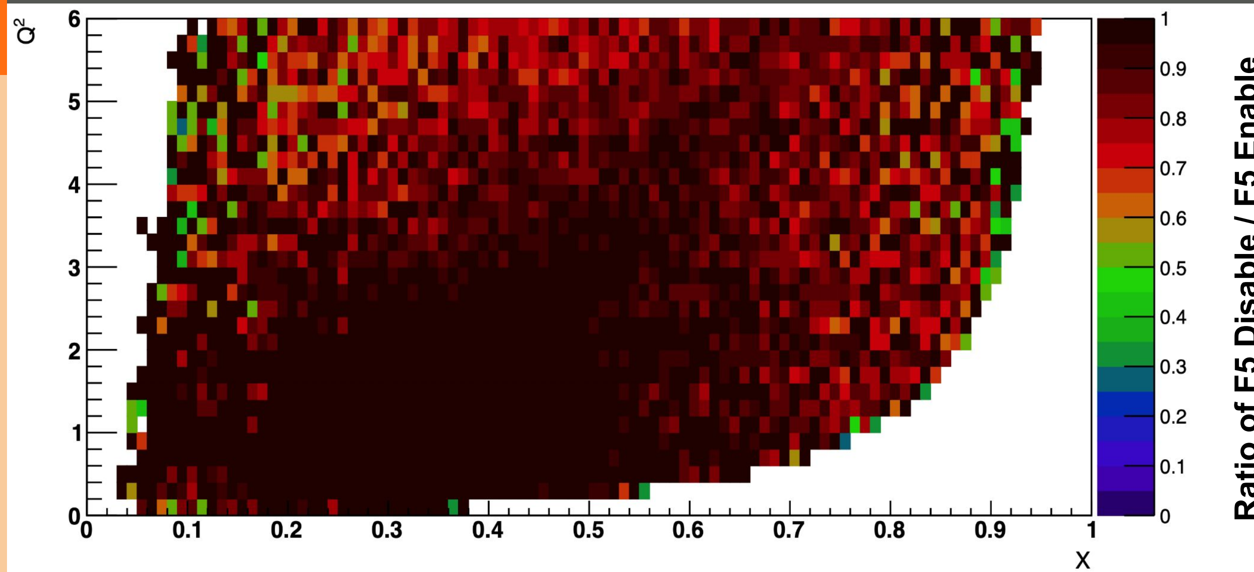


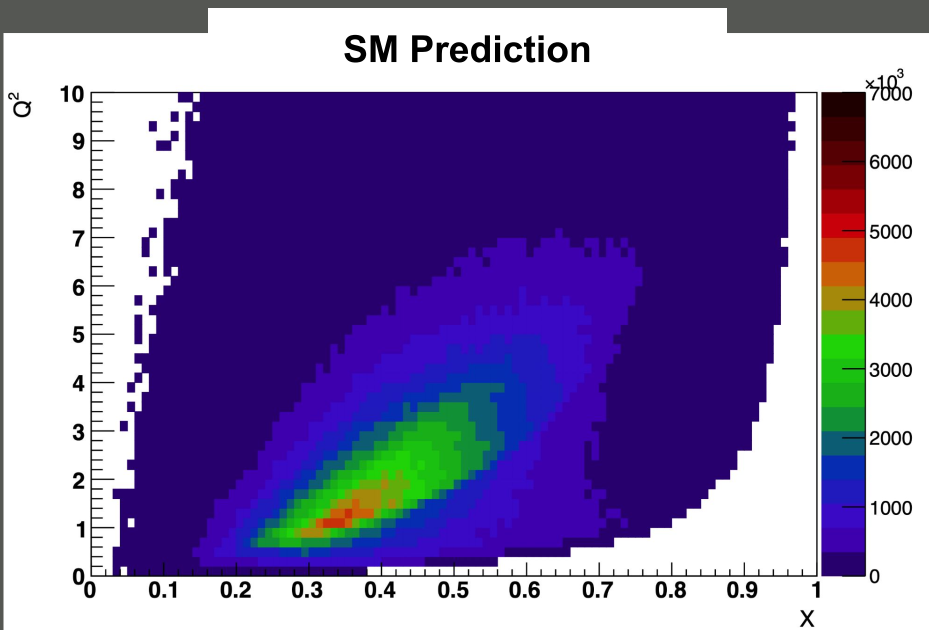
What about the effect of F_5 in the total number of events?

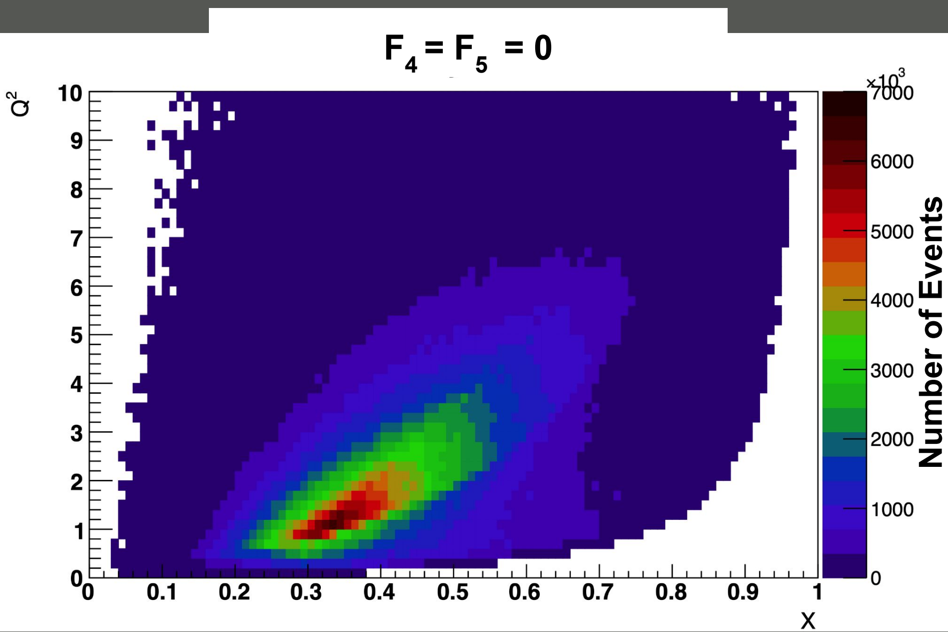
The ratio is greater than 1:

- Which is expected since F_5 is a subtracted component of the total XSec.
- Also, it means that there is a chance to disentangle an overall normalization change from a scaling of F_5

F_5 covers all the phase space (Q^2, x)







So Far

The new features which appear in the case of the ν_τ–A interaction as compared to the ν_e and ν_μ interactions and contribute to modify the cross sections are:

- Kinematical changes in Q^2 and E_ℓ due to the presence of m_τ
- The contributions due to the additional nucleon structure functions F_4 (x,Q^2) and F_5 (x,Q^2) in the presence of $m_\tau \neq 0$.
- As a function of Q^2 , there is an enhancement doesn’t come just from a normalization but due the changes on the shape the presence of m_τ

Some of the above effects are modified in the nuclear medium → we need reliable nuclear model to describe DIS of leptons from nuclear targets.

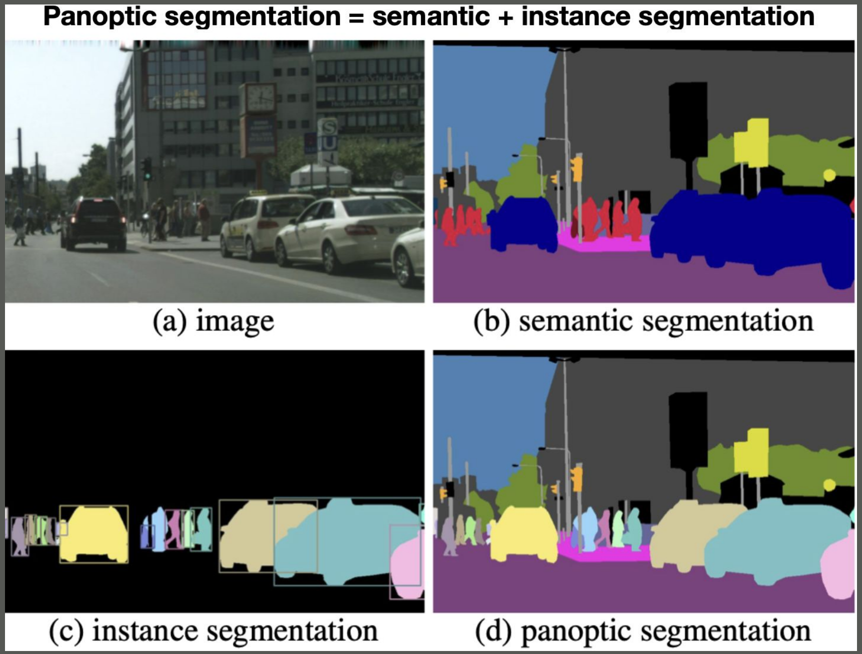
Get a reliable kinematic reconstruction it’s a must!

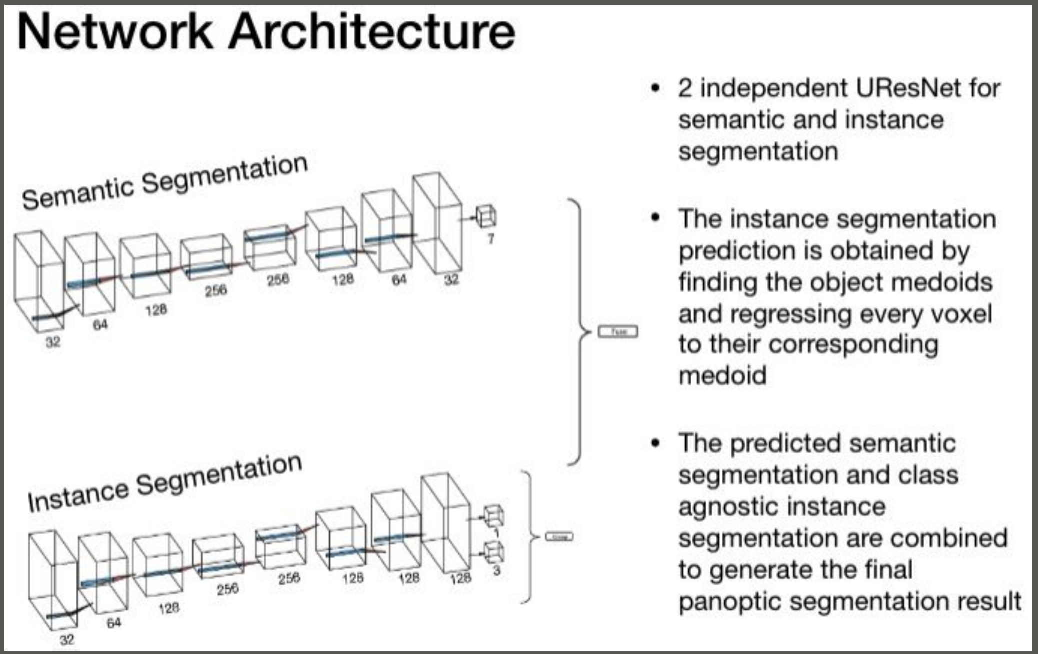
We are checking on machine learning techniques...

Panoptic Segmentation: Semantic + Instance Segmentation

by Carlos Sarasty sarastce@mail.uc.edu "Panoptic Segmentation for Particle ID in ProtoDUNE"

- **Semantic segmentation** is the process of assigning a class label to each pixel
- **Instance segmentation** is the task of detecting objects in the image





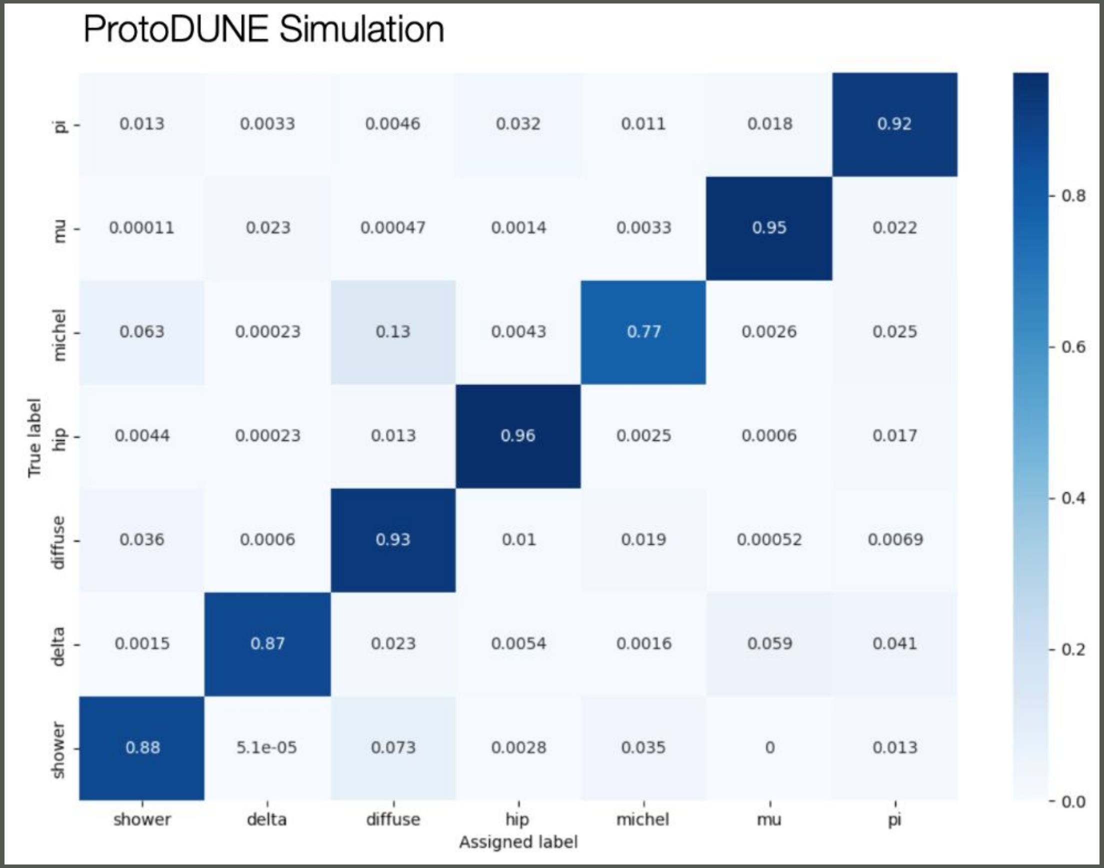
arXiv:1801.00868

Results/Metrics: Semantic Segmentation

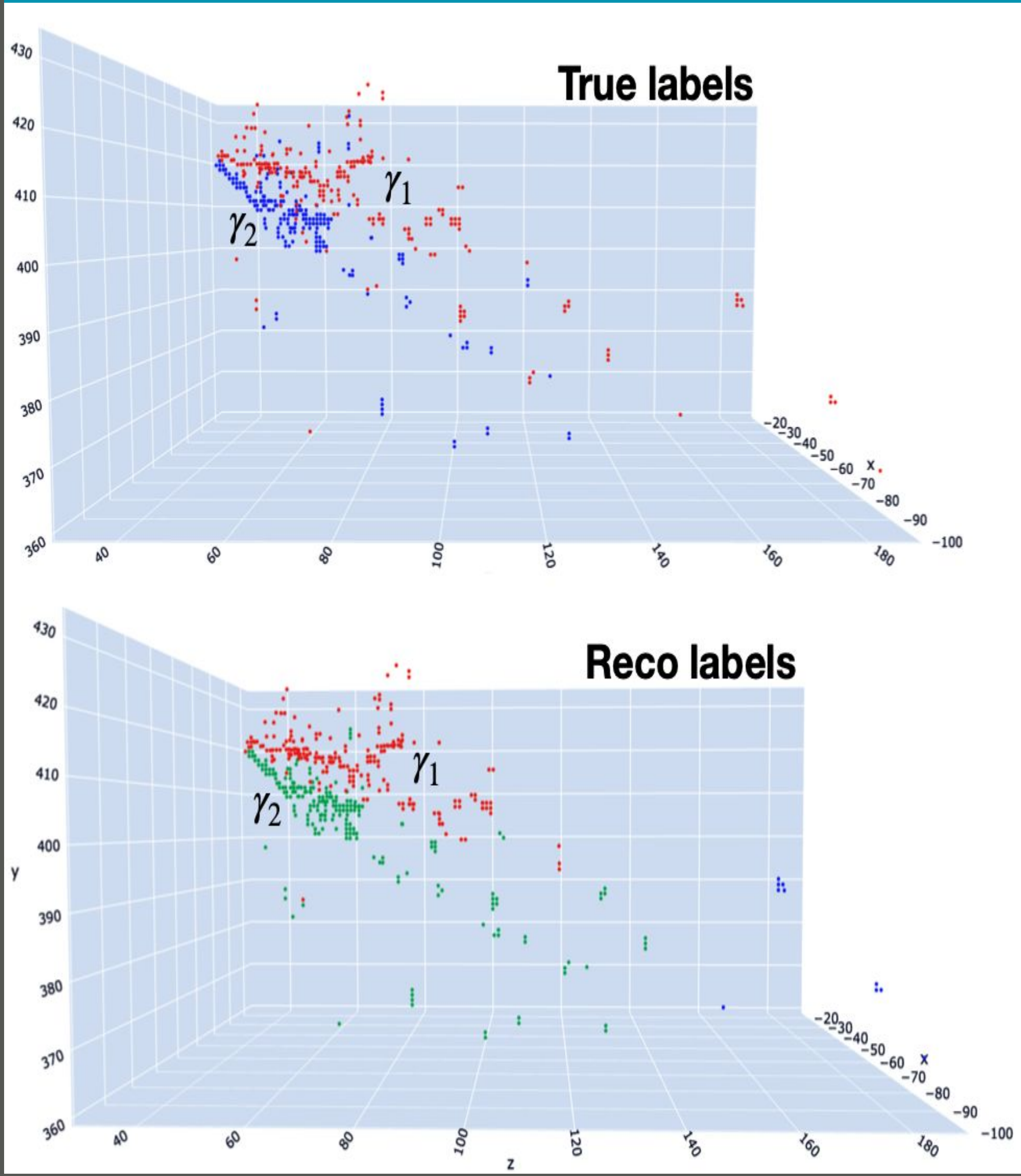
ProtoDUNE by Carlos Sarasty sarastce@mail.uc.edu

- **The network is capable to identify shower like and track like separation with high accuracy**

- **The confusion matrix shows the overlap between classes**



Event Display: two showers from neutral pion decay



Outlook

- **DUNE** will provide a **unique opportunity** to study the connections among neutrinos.

- **Tau neutrinos** will help us understand whether or not the **PMNS matrix** is unitary.

- **Improve our nuclear models:**

  There are models in which they single out the tau neutrino to satisfy other constraints, and in other cases, the model does not depend on the flavor of the neutrino, but tau neutrinos may be the only means of probing the model.

- **Tau neutrinos** play a central role in **testing the lepton flavor universality** violating hints uncovered in flavor physics experiments.

Thank you!

Backup

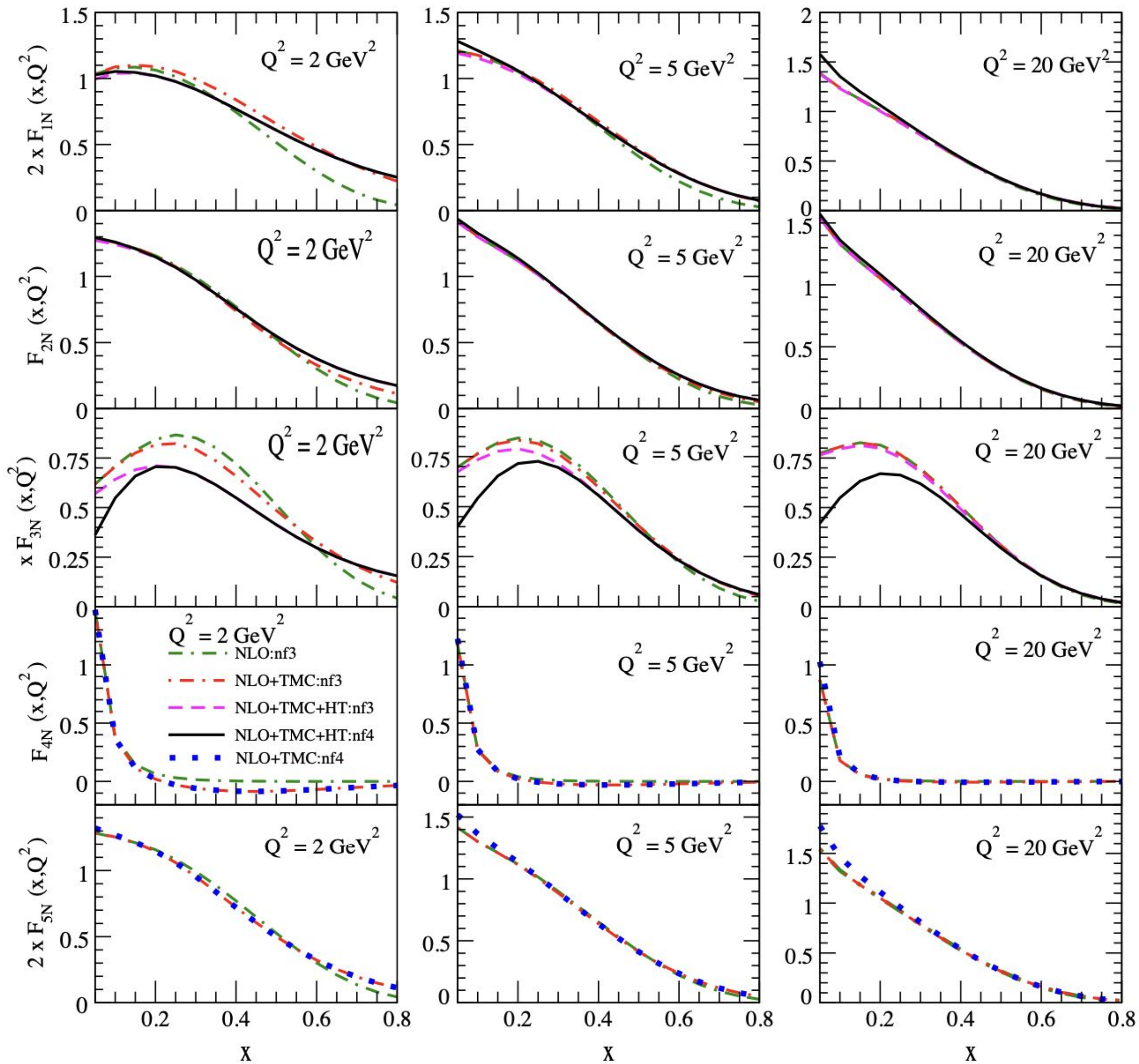
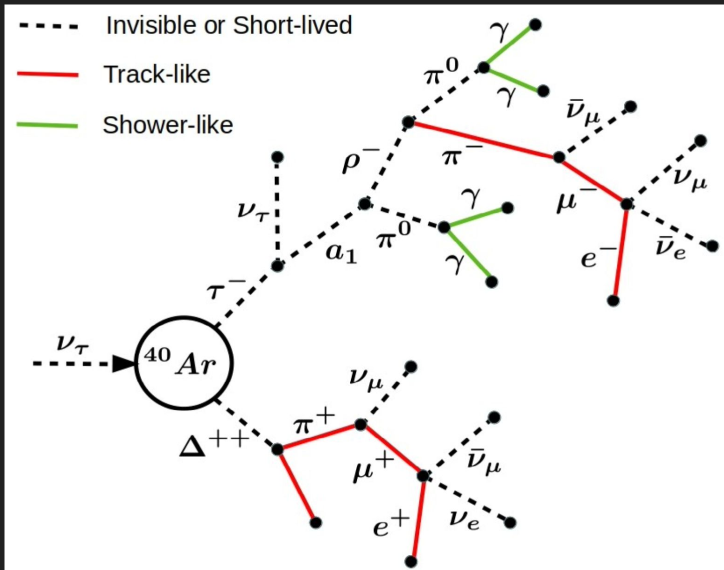
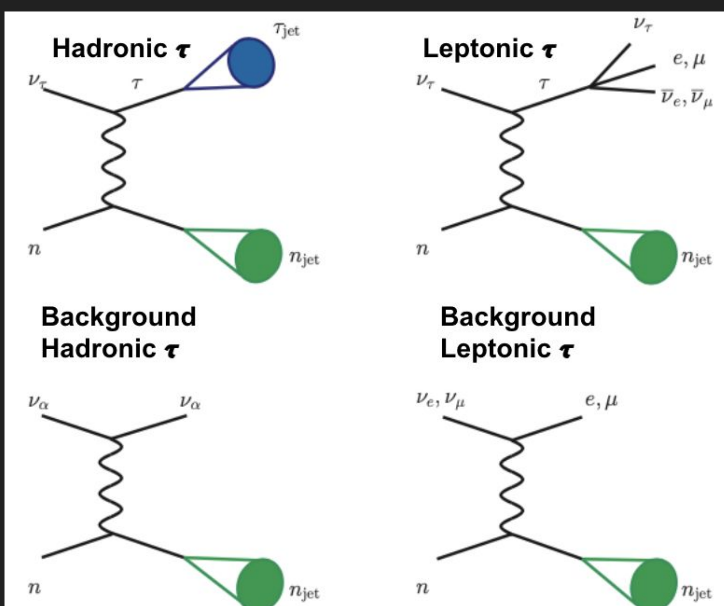


FIG. 3. Results for the free nucleon structure functions $F_{iN}(x, Q^2)$; $(i = 1\text{–}5)$ (top to bottom) at the different values of Q^2 viz. 2, 5 and 20 GeV^2 (left to right) are shown. These results are obtained at NLO by using MMHT nucleon PDF parametrization [32]. The results are shown without the TMC effect (double dash-dotted line), with the TMC effect in the three-flavor (nf3) scheme (dash-dotted line) as well as four-flavor (nf4) scheme (dotted line), with TMC and HT effects in the three-flavor (nf3) scheme (dashed line) as well as four-flavor (nf4) scheme (solid line).

A key element in the study of tau neutrino physics is the decay modes of the tau lepton





Tau decay length ~ 87 μm
^{40}Ar nuclear radius, ~ 3.4 fm

→ Tau decay products aren't subject to the ^{40}Ar nuclear potential

Tau lifetime (2.903±0.005) ×10^{-13} s
Mass: 1.7 GeV/c^2

→ Tau doesn't lead to observables displaced vertices

DUNE granularity is limited by wire spacing of a few millimeters

Observation of Tau tracks is unlikely

Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
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$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
other	5.7%

Background for τ_μ signal mainly comes from CC-ν_μ being ν_μ flux very large.

Background for τ_e signal are CC-ν_e events, being ν_e flux a small fraction of the total neutrino flux.

. P.Machado, J.Turner. H. r Schulz
arXiv:2007.00015

Why Structure functions are written in terms of the scaling variable x and Q^2, rather than the energy transfer Eν and Q^2?

Because for fixed x values of $F_1 \ldots F_5$ become ~ independent of Q^2 , or $F_{1,\ldots,5}(x, Q^2)=F_{1,\ldots,5}(x)$ is a good approximation for a large Q^2.

This behavior is called Bjorken scaling, or scale invariance: the structure functions are left unchanged by a scale transformation.

ν_τ (CC) interactions give access to cross section physics not accessible otherwise!

Inelastic Scattering: since the lepton and hadronic system do not interact after scattering, can factorize the cross-section into leptonic & hadronic tensors

$$\frac{d^2\sigma_A}{dxdy} = \left(\frac{G_F^2 y M_N E_l}{2\pi E_\nu}\right)\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{|\mathbf{k}'|}{|\mathbf{k}|} L_{\mu\nu} W_A^{\mu\nu}$$

$$L_{\mu\nu} = 8(k_\mu k'_\nu + k_\nu k'_\mu - k.k' g_{\mu\nu} \pm i\epsilon_{\mu\nu\rho\sigma} k^\rho k'^\sigma)$$

Summing over spins, and assuming parity conservation, we can write the most generic form of the hadronic tensor:

$$W_A^{\mu\nu} = \left(\frac{q^\mu q^\nu}{q^2} - g^{\mu\nu}\right) W_{1A}(\nu_A, Q^2) + \frac{W_{2A}(\nu_A, Q^2)}{M_A^2}\left(p_A^\mu - \frac{p_A . q}{q^2} q^\mu\right)\left(p_A^\nu - \frac{p_A . q}{q^2} q^\nu\right) \pm \frac{i}{2M_A^2}\epsilon^{\mu\nu\rho\sigma} p_{A\rho} q_\sigma W_{3A}(\nu_A, Q^2)$$
$$+ \frac{W_{4A}(\nu_A, Q^2)}{M_A^2} q^\mu q^\nu + \frac{W_{5A}(\nu_A, Q^2)}{M_A^2}(p_A^\mu q^\nu + q^\mu p_A^\nu) + \frac{i}{M_A^2}(p_A^\mu q^\nu - q^\mu p_A^\nu) W_{6A}(\nu_A, Q^2),$$

Lorentz-invariant variables:

$$Q^2 \equiv -q^2 = -(k-k')^2 = 4EE'\sin^2(\theta/2)$$
$$\nu \equiv \frac{p\cdot q}{M} = E - E'$$

$$W^2 \equiv (p+q)^2 = M^2 + 2M\nu - Q^2$$

Structure Functions

→ A Structure function characterize the internal structure of the nucleon

→ The contributions of the structure functions to the cross-section are functions of charged lepton mass.

→ In the limit $m_l^2 \to 0$ only F_1, F_2 and F_3 contribute, $m_l^2/(M_N E_\nu)$.

→ Structure functions F_4 and F_5 are negligible for ν_μ and ν_e, but become important for ν_τ

$$\frac{d^2\sigma_A}{dxdy} = \frac{G_F^2 M_N E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\left\{\left[y^2 x + \frac{m_l^2 y}{2E_\nu M_N}\right] F_{1A}(x,Q^2) + \left[\left(1 - \frac{m_l^2}{4E_\nu^2}\right) - \left(1 + \frac{M_N x}{2E_\nu}\right) y\right] F_{2A}(x,Q^2)\right.$$
$$\left. \pm \left[xy\left(1-\frac{y}{2}\right) - \frac{m_l^2 y}{4E_\nu M_N}\right] F_{3A}(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x} F_{4A}(x,Q^2) - \frac{m_l^2}{E_\nu M_N} F_{5A}(x,Q^2)\right\}$$

The scaling variables $x(=\frac{Q^2}{2p\cdot q})$ and $y(=\frac{\nu}{E_\nu}=\frac{q_0}{E_\nu})$ lie in the range:

$$\frac{m_l^2}{2M_N(E_\nu - m_l)} \le x \le 1 \qquad \text{and} \qquad a - b \le y \le a + b,$$

where

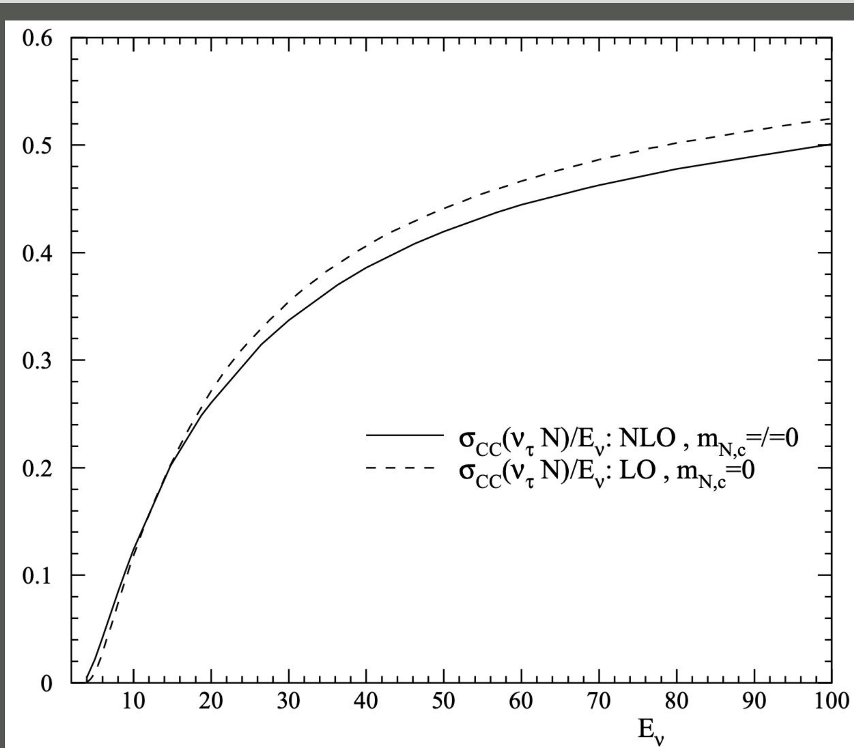
$$a = \frac{1 - m_l^2\left(\frac{1}{2M_N E_\nu x} + \frac{1}{2E_\nu^2}\right)}{2\left(1+\frac{M_N x}{2E_\nu}\right)} \qquad \text{and} \qquad b = \frac{\sqrt{\left(1 - \frac{m_l^2}{2M_N E_\nu x}\right)^2 - \frac{m_l^2}{E_\nu^2}}}{2\left(1+\frac{M_N x}{2E_\nu}\right)}.$$

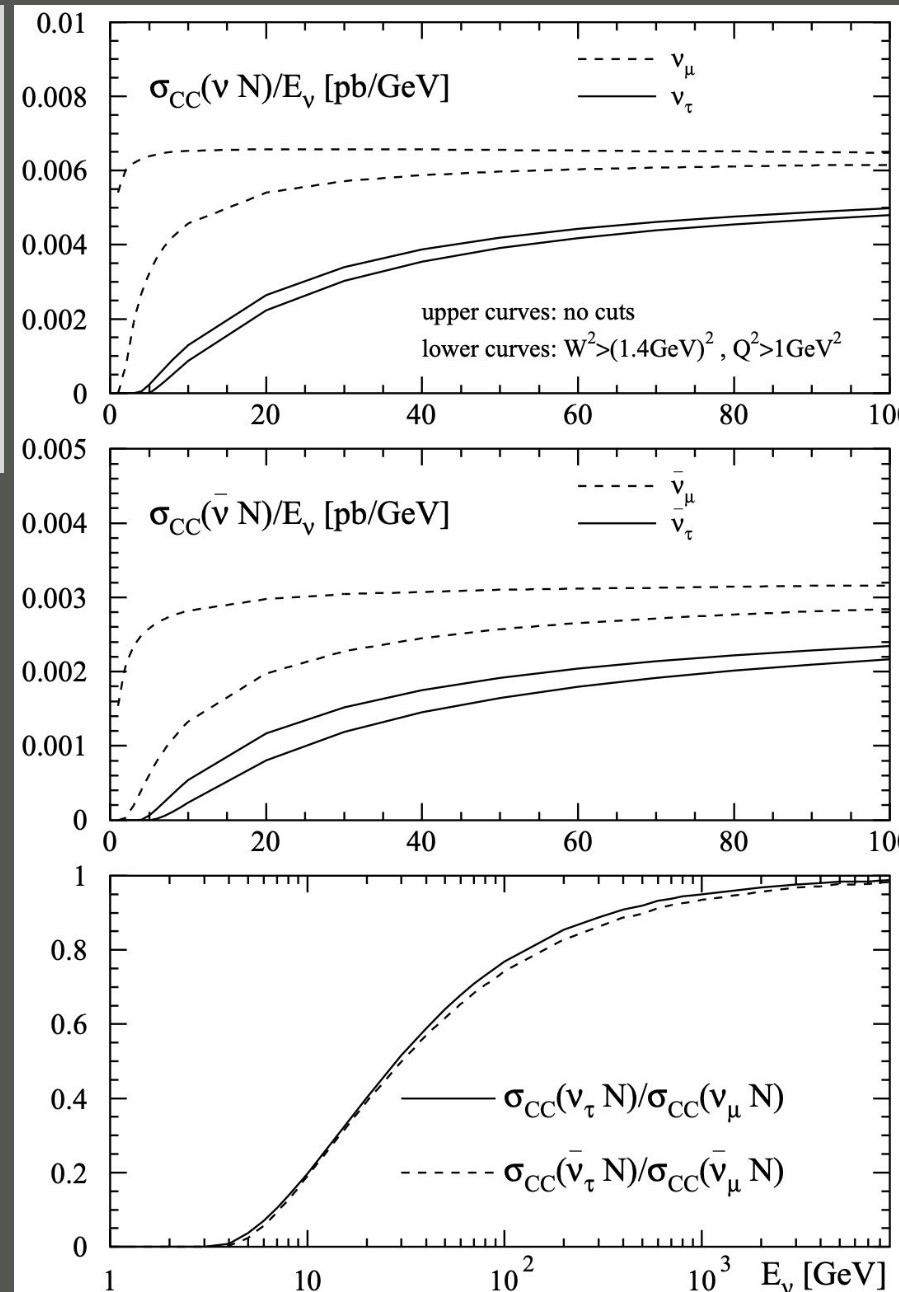
For quasielastic scattering, **e.g., $\nu_\tau \to \tau p$,** the structure functions are proportional to the delta function **$\delta(W^2 - M^2)$** where W^2 is the invariant mass of the hadronic final state. These multiply the nucleon form factors ← **Avoid double counting we impose W_{min} = 1.4 GeV.** Phys. Rept. 3, 261 (1972) Phys. Lett. B 564, 42 (2003)

Reasons for the deficit in the ν_τ CC cross-section:

1) The **reduce phase space: integration limits (x,y),** half of the suppression of ν_τ relative to the ν_μ it is from a dynamic origin.

2) F_5 minus sign and no factor of x: $$-\frac{m_\tau^2}{E_\nu M_N}F_5^{W^\pm}$$





A look to the CC ν_τ and ν_μ Cross Section M. H. Reno - PhysRevD.74.033001

Reasons for the deficit in the ν_τ CC cross-section:

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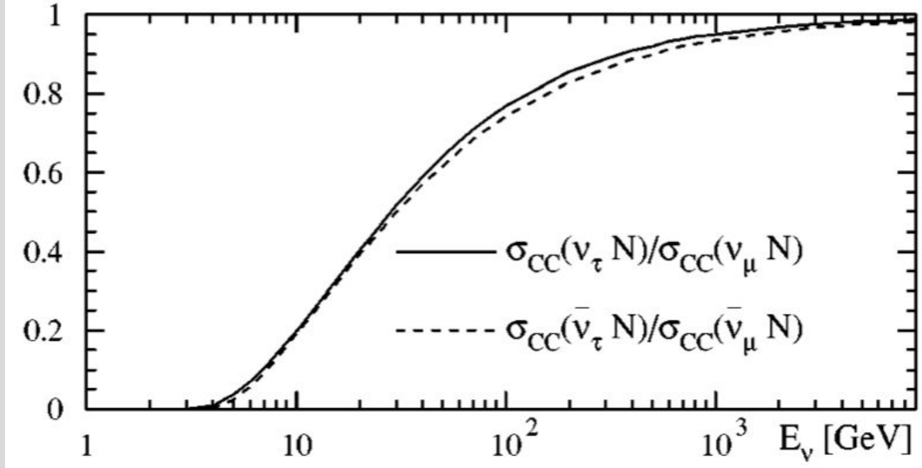
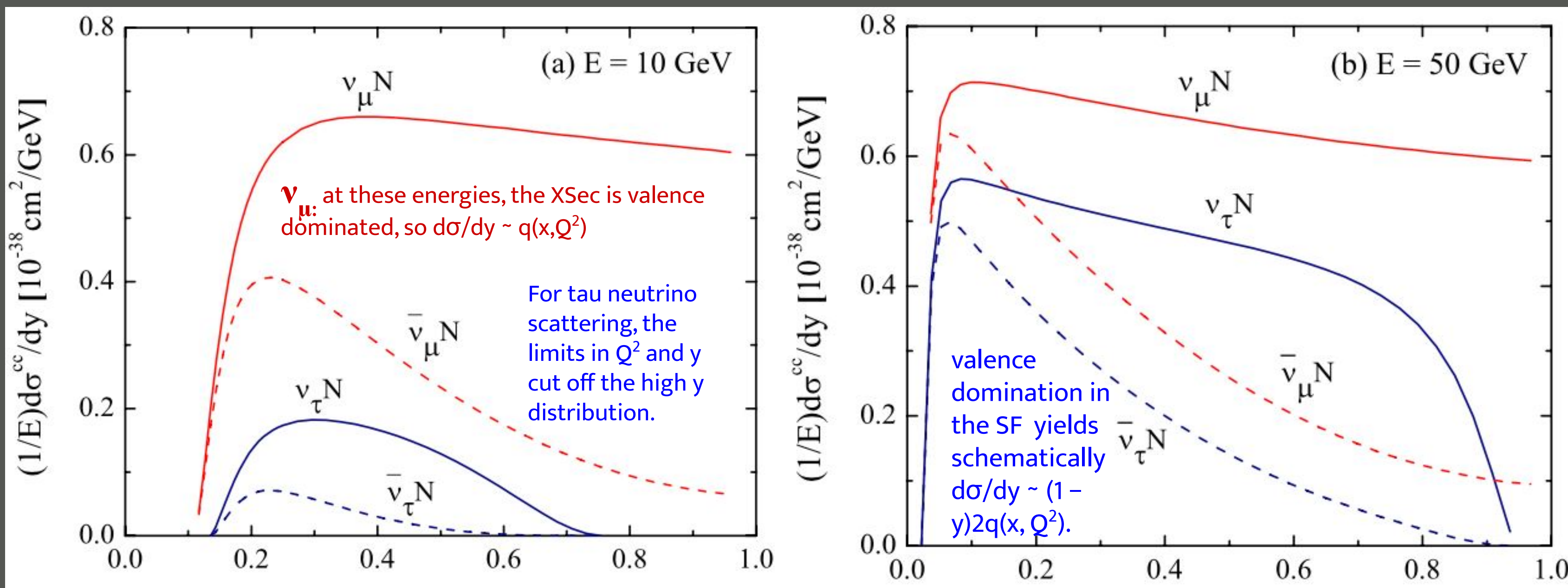
Since $F_5 \sim F_1 \sim q(x, Q^2)$ there is a small-x enhancement of its contribution to the cross section at high energies.



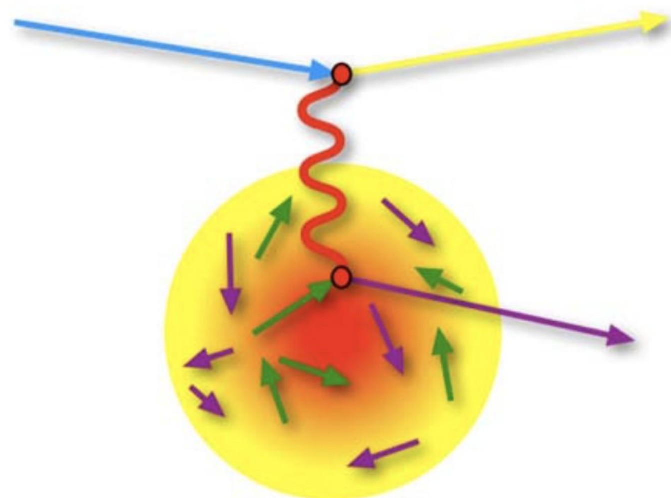


arXiv:1007.1966v1

The kinematic effects of producing a tau lepton are less noticeable.

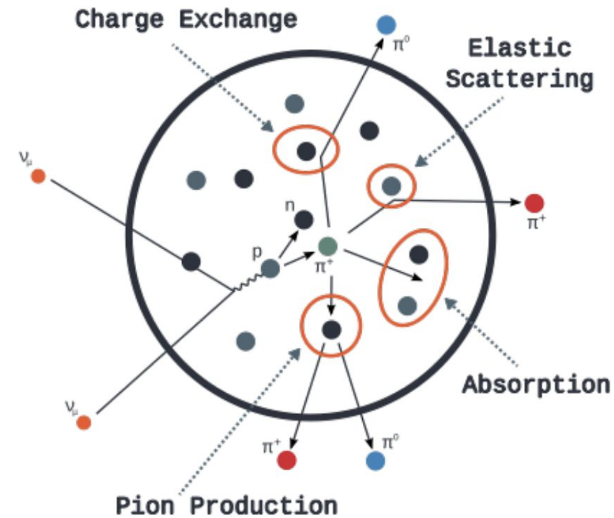
Don't Forget Nucleus! - Study Nuclear Effects

Initial State Nuclear Effect



- Short, medium, and long range nucleon-nucleon correlations on the initial condition, e.g. "2p2h" effect , "RPA" effect

Final State Nuclear Effect



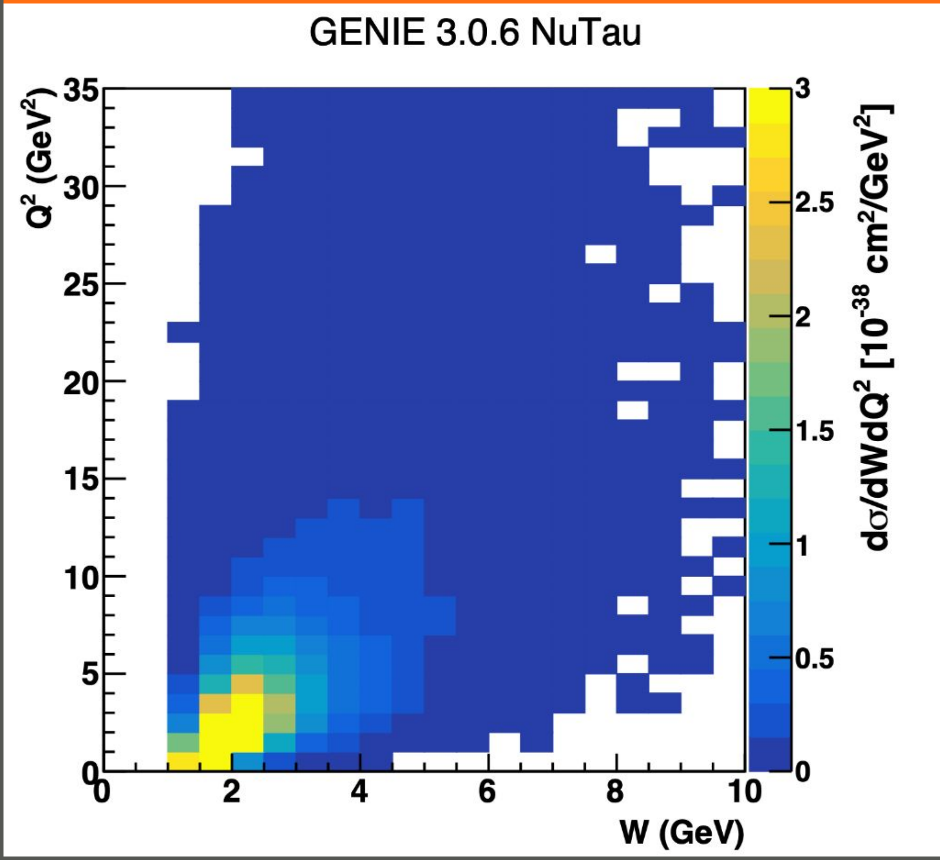
- Particles created have to work their way out of the nucleus, e.g. absorption

Signal ↔ Background Migration

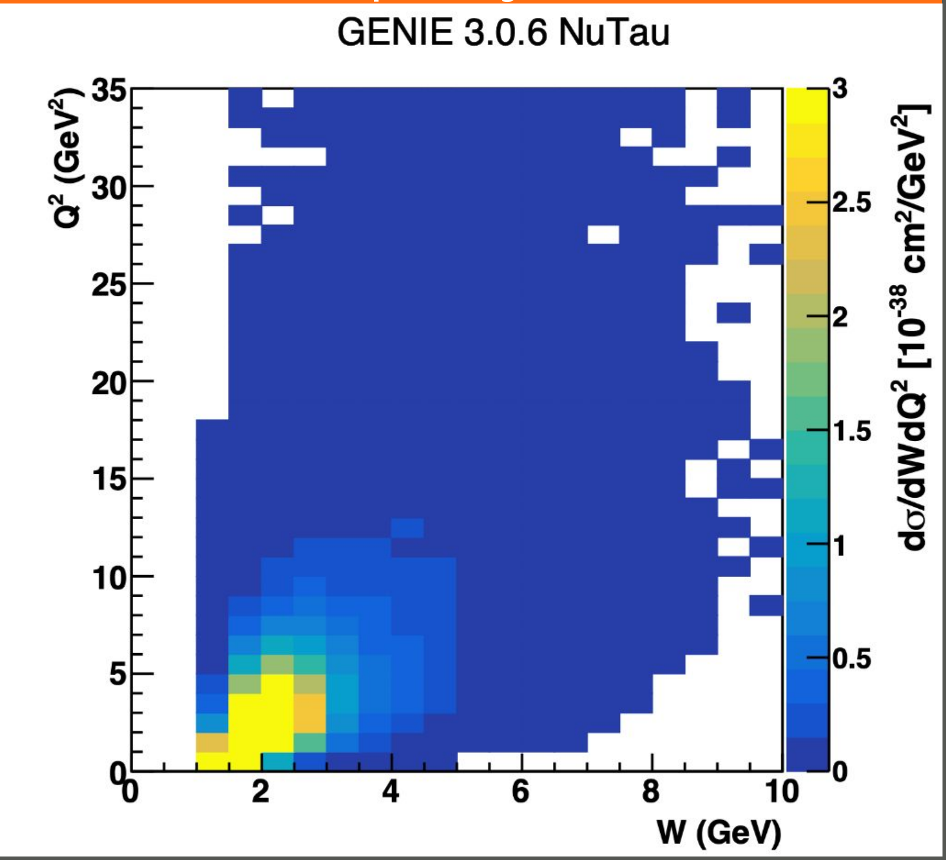
CC - ν_τ TRUTH Level studies show that indeed, when DIS cuts are applied and $F_5 = 0$ we can extract new information from the lepton cross section.

ν_τ

SM Prediction



$F_4 = 0, F_5 = 0$



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ν_τ

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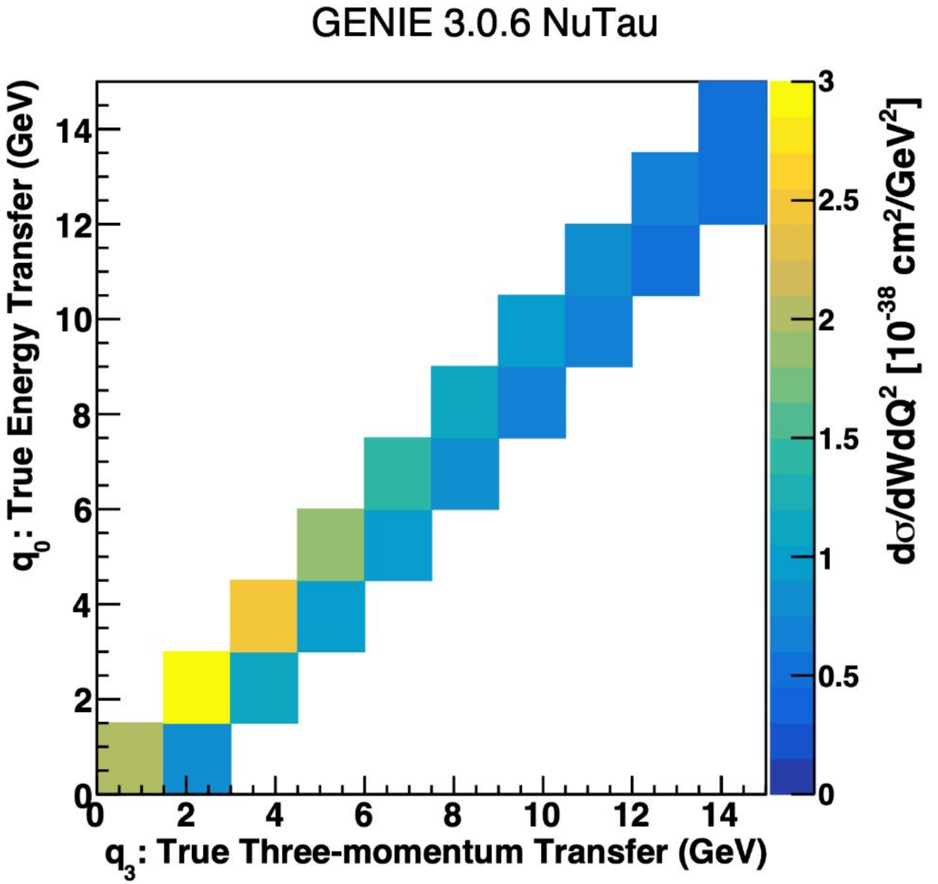

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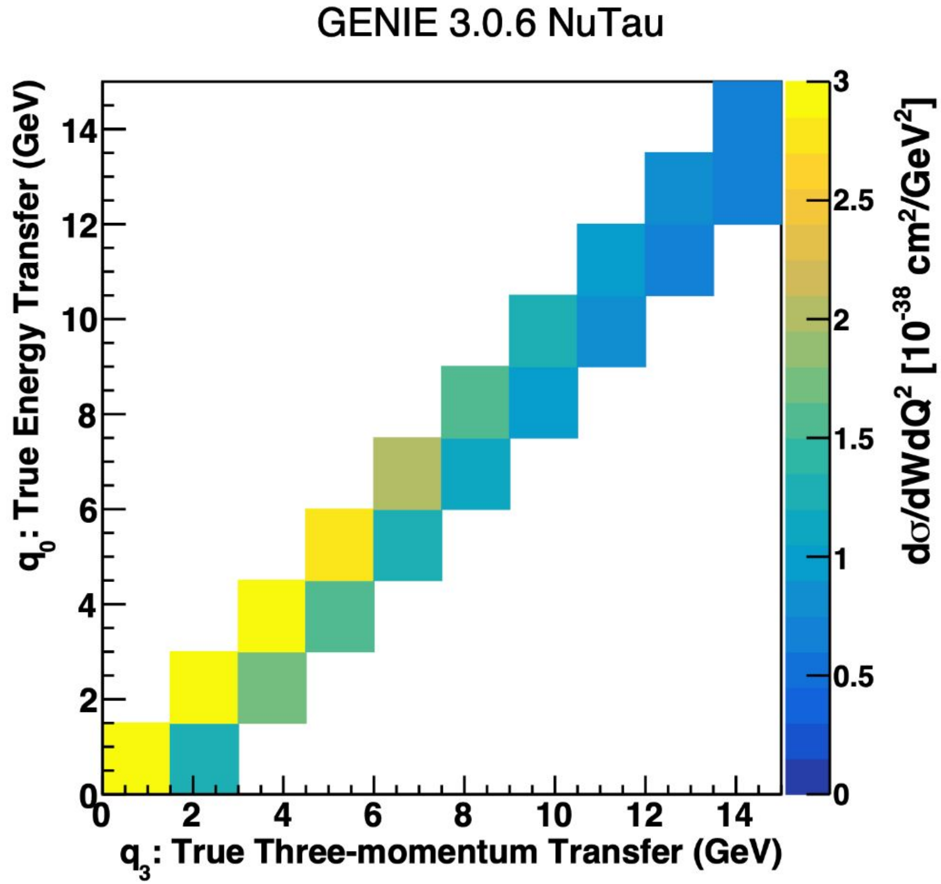

Results/Metrics: Instance Segmentation

ProtoDUNE by Carlos Sarasty sarastce@mail.uc.edu

- **Purity:** Is the fraction of reconstructed medoids that are no more than 7 cm from the true medoid. ~ 81.3%

- **Efficiency:** Is the fraction of true particles with at least one reconstructed particle ~84.2%

Results/Metrics: Panoptic Segmentation

ProtoDUNE by Carlos Sarasty sarastce@mail.uc.edu

- **Purity:** Is the fraction of voxels in the reconstructed particles shared with the true particle. ~ 60.1%

- **Completeness:** Is the fraction of true voxels that are shared with the reconstructed particle. ~ 70.2%